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E-301

TMX 59653
Page 30

TURBOPUMPS FOR HIGH-ENERGY PROPELLANTS

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INTRODUCTION

Man's exploration of space depends greatly on his ability to put heavier payloads into the space environment. The high-energy liquid propellants appear attractive as a means for improving rocket payload and mission capability. Much has been written in recent literature concerning rockets using the high-energy liquid propellants, their potential impulse, and their comparative payloads. Such comparisons must consider rocket staging, structural efficiency, and mission requirements. It is not the intent of this paper to attempt such evaluations. This paper is concerned with the turbopumps to be used with these high-energy liquid propellants. Three chemical propellant combinations will be considered: hydrogen and oxygen, hydrogen and fluorine, and for comparative purpose, RP1 and oxygen. Also to be considered will be heated hydrogen for nuclear rocket applications.

As evident by the propellant combinations to be considered, hydrogen is the fuel of interest. The use of hydrogen with its low molecular weight as compared with the oxidants and conventional fuels creates a different pumping problem which can result in changes in turbopump design concepts. This paper will describe the general characteristics of these hydrogen-fuel turbopumps and discuss differences in the basic components, namely, pumps, drive turbine, and gearing.

SYMBOLS

A_F	frontal area, ft^2
c_p	specific heat at constant pressure, $Btu/lb/^{o}R$
g	acceleration due to gravity, ft/sec^2
H	head rise across pump, ft
H_{sv}	net positive suction head, ft
h'	turbine-inlet total enthalpy, ft-lb/lb
$\Delta h'$	specific work, ft-lb/lb
J	mechanical equivalent of heat, ft-lb/Btu
K	constants
N	number of pump or turbine stages
n	rotative speed, rpm
P_G	gearing power
P_r	turbine total-to-static pressure ratio
P_{sv}	net-positive suction pressure, lb/ft^2
p	pressure, lb/ft^2
Q	volume flow rate, gal/min
R	gas constant, $ft/^{o}R$
SS	suction specific speed
T	turbine-inlet total temperature
U	average pump-rotor-exit blade speed, mean-section turbine blade speed, ft/sec
V_u	tangential component of velocity, ft/sec
W	weight, lb
w	weight flow rate, lb/sec
γ	ratio of specific heats
η	pump or turbine efficiency

ν specific volume, ft^3/lb

ψ pump and turbine stage diagram parameter, $\Delta V_u/U$

ω angular velocity, rad/sec

Subscripts:

b bulk

f fuel

id ideal

o oxidant

P propellant

p pump

T turbine

tot total

OVER-ALL TURBOPUMP CONSIDERATIONS

A description of the major turbopump components and relation of the turbopump to the rocket fluid flow system can be made using figure 1 where a schematic diagram of a typical chemical system is presented. The fuel and oxidant pass from the tanks and enter their respective pumps. As the flow passes through the pumps its pressure is raised to the level required to meet the thrust-chamber pressure requirements. After discharge from the pumps the flow is passed to the thrust-chamber area. A small percentage of both fuel and oxidant is seen to be bled off downstream of the pumps and directed to a gas generator where the two propellants are burned. The product of combustion (usually fuel rich) is then passed through the drive turbine where the energy required to provide the necessary pump power is extracted. Upon discharge from the turbine the gases are exhausted overboard.

E-301

The turbine is shown connected to both pumps through gearing, because these components, in general, desire to operate at different rotative speeds.

The turbopump affects the rocket performance in two ways. First, the flow that is diverted through the turbine reduces the rocket specific impulse, considered herein as the ratio of thrust to total-propellant-consumption rate. ~~and~~ Thus, [redacted]. For a given structural weight, this would then mean a reduction in payload. Second, the turbopump weight, also being part of the empty weight, is significant as changes in its value result in corresponding required changes in payload.

These two characteristics, turbine flow rate and turbopump weight, are, in general, related to each other through the turbopump efficiency considered herein as the product of the pump and turbine efficiencies. A reduction in flow rate is obtained through an increase in efficiency. However, in general, this improved efficiency is obtained at the expense of increased turbopump weight, primarily in the area of the turbine. In view of this counterbalancing effect, it is of interest to know the relative significance of these two factors so that the desired direction, high efficiency or low weight, can be established. Such a comparison is made in figure 2 for an example high-energy-propellant application. Percent increase in turbine flow rate is presented as a function of percent increase in turbopump weight. The line represents the relation between these two factors that yields no net change in the ratio of rocket payload to gross weight. It can be seen that, for this example, a 20-percent increase in flow rate must be matched by a 60-percent reduction in turbopump weight. Since the curve is almost a straight line, these numbers can be interpreted as indicating a ratio of weight to flow rate of 3 to 1. From these considerations, it is evident that low flow rates are desired, even at the expense of some turbopump weight. Through the relation of flow rate to efficiency, it is then indicated that high component efficiencies are desired. Although thrust recovery of the turbine exhaust gases was not considered in the foregoing example, the same general conclusion would be reached.

PUMP CONSIDERATIONS

The purpose of the pump is to increase the fluid pressure level from that in the tank to that required to establish the thrust chamber pressure. A wide range of design parameters can be considered with the final selection being based on the requirements of efficient operation and light weight. This section will present a discussion of the effects of the high-energy propellants being considered herein on pump hydrodynamic design, as well as pump size and weight characteristics.

The pump pressure characteristics are usually described in terms of head of fluid. The head rise across the pump can in this way be related to its pressure rise by the equation:

$$H = \Delta p_p \nu \tag{1}$$

This value of head is also equal to the ideal specific work input which can be expressed in terms of the pump-stage velocity diagrams as shown in the next equation:

$$H = \eta \Delta h' = \frac{\eta U \Delta V_u N}{g} \tag{2}$$

The tangential velocity (V_u) at the pump inlet is assumed equal to zero. The combination of equations (1) and (2) and use of a stage diagram parameter ψ, where ψ is equal to $\Delta V_u/U$, results in the following equation:

$$\Delta p_p = \frac{\eta (U^2 \psi N)}{g \nu} \tag{3}$$

The high-energy propellants represent a very wide range of fluid specific volumes as illustrated in figure 3. Liquid fluorine has a specific volume near 0.01 and liquid hydrogen has a specific volume near 0.22. For the following discussion, RP1, Oxygen (O_2), and fluorine (F_2) will be considered as being of low specific volume, whereas hydrogen (H_2) will be considered as being of high specific volume.

E-301

From equation (3), for a given pump pressure rise,

$$\nu = K\eta(U^2\psi N) \tag{4}$$

For a given efficiency, the product in parentheses must vary directly as the specific volume of the fluid, and encounters a range of 22 to 1 between the heavy fluids RP1, O_2, and F_2 and the light fluid hydrogen.

Pump designs for the low specific volume fluids require a relatively low value of the product $(U^2\psi N)$. Thus, single-stage pumps with moderate values of both rotor-blade speed U and ψ can be utilized to obtain the required pump pressure rise. These pumps utilize backward swept blades with ψ values of the order of 0.5. Even with low values of ψ the rotor-blade speeds to obtain the required head rise will be well below the desired turbine speeds. A single-stage pump of this type is shown schematically in figure 4(a). Pumps of this type are in use in current turbopump designs.

A single-stage pump similar to the heavy-fluid pump shown in figure 4(a) could be used for hydrogen by increasing the rotor-blade speed U by the maximum ratio of approximately 22 to 1. In general, an increase in U of this magnitude cannot be achieved because of rotor stress limitations. Thus, single-stage hydrogen pumps will utilize both high values of the diagram parameter ψ and a high rotor-blade speed U. A pump of this type

E-301

is shown in figure 4(b). The pump is a radial-blade centrifugal unit operating at a ψ value of 1.0. Configurations similar to this type are required for a rotor design utilizing high values of ψ. It should be noted that the rotor-tip radius is large compared with the inlet radius.

Greater flexibility in the design of hydrogen pumps exists if the design is not limited to single-stage rotors. A two-stage hydrogen pump as shown in figure 4(c) would make possible a reduction in both the tip radius and the diagram parameter ψ. A third hydrogen-pump configuration is shown in figure 4(d) where numerous axial stages having relatively low values of ψ are used. The three pump types shown for the hydrogen case may have different efficiency characteristics due to stage losses (which are a function of ψ), as well as interstage losses incurred for the multiple-stage units. Since, as pointed out previously, high pump efficiencies are desired, the final selection of pump configuration would probably be made on this basis.

Another hydrodynamic-pump design consideration is the cavitation problem. The tendency for a pump to cavitate is usually judged from the similarity parameter, suction specific speed, defined as

$$SS = \frac{n\sqrt{Q}}{(H_{sv})^{3/4}} \tag{5}$$

which relates the rotational speed, volume flow rate, and inlet net-positive suction head. Conventional practice in pump design fixes the limit of pump operation at incipient cavitation, with associated limiting values of suction specific speeds of the order of 10,000. For rocket engine application, in order to meet the pressure requirements with small lightweight pumps, it is necessary to go to suction specific speeds over this limit. Pumps which can tolerate cavitation without undue losses in efficiency have been

E-301

developed. Careful design ~~has~~ can produce~~d~~ pump rotors which operate at suction specific speeds of the order of 30,000.

Since $H_{sv} = P_{sv}\nu$, equation (5) can be written as:

$$SS = \frac{n\sqrt{Q}}{(P_{sv})^{3/4}(\nu)^{3/4}} \tag{6}$$

From this equation the large effect of fluid specific volume on rotational speed can be observed. The high specific volume of liquid hydrogen allows the use of high rotational speeds n without exceeding a given limit of suction specific speed. However, the pump configurations required for hydrogen can limit the potentially higher rotational speed due to rotor stress. Thus, because of this stress limitation, hydrogen pumps may not be able to utilize the high suction specific speeds. This is especially true for the radial-flow centrifugal pump shown in figure 4(b). The smaller tip-diameter, two-stage hydrogen pump more nearly utilizes the high suction specific speed, whereas the multistage axial-flow pump may easily utilize a limiting suction specific speed. On the other hand, the pump configuration suitable for the low specific volume fluids does not impose this stress limitation and therefore, high limiting suction specific speeds can be utilized.

The pump size and weight characteristics will be discussed on a per unit pump flow and on a per unit propellant flow basis. With these characteristics known on a specific basis, it is easy to convert them to actual-size comparisons.

Pump weight studies have shown it to be a function of frontal area and number of stages. That is,

$$W_p = KA_{F,p}N \tag{7}$$

E-301

Dividing through by w_p yields

$$\frac{W_p}{w_p} = K \frac{A_{F,p}}{w_p} N \tag{8}$$

Now the frontal area of the pump is related to U and the rotative speed by the equation

$$A_{F,p} = \pi \frac{U^2}{\omega^2} \tag{9}$$

The use of equations (3) and (6) in equation (9) with appropriate modification yields

$$\frac{A_{F,p}}{w_p} = \frac{K}{\eta}\left(\frac{\Delta p_p}{P_{sv}^{3/2}}\right)\frac{\nu^{1/2}}{\psi N(SS)^2} \tag{10}$$

Thus, if Δp_p, P_{sv}, and η are assumed constant, then

$$\frac{A_{F,p}}{w_p} = K \frac{\nu^{1/2}}{\psi N(SS)^2} \tag{11}$$

Substituting equation (11) into (8) yields

$$\frac{W_p}{w_p} = K \frac{\nu^{1/2}}{\psi (SS)^2} \tag{12}$$

Comparison of the pump size and weights on a per unit pump flow basis can be made using equation (12) where for the RP1, O_2, and F_2 cases ψ is assumed equal to 0.5 and SS is at its limiting value. For this comparison, the hydrogen pump is assumed to use a $\psi = 1$ with the associated SS reduced to one-half the limit used for the dense fluids. As discussed previously, a reduction of SS would probably be encountered for this type of pump as a result of the pump stress limits. Because of the counterbalancing effect of ψ and SS in equation (12), it is felt that the comparative results obtained using this pump are representative of those to be obtained for the multistage units. Comparative size (in terms of frontal area) and weight characteristics obtained on this basis are presented in figure 5. Here it is seen that the specific sizes and weights of the dense fluids are comparable in level. The hydrogen pump, on the other hand, is approximately eight times the size and weight of the heavy fluid pumps.

A comparison of the weights on a per unit propellant flow basis can be made using the following equation which relates the pump specific weight defined by equation (12) to the total pump specific weight

$$\frac{W_{p,tot}}{w_P} = \frac{W_f}{w_f}\left(\frac{w_f}{w_P}\right) + \frac{W_o}{w_o}\left(1 - \frac{w_f}{w_P}\right) \tag{13}$$

where w_f/w_P or ratio of fuel flow rate to total-propellant flow rate must be selected for the propellant combination considered. Comparative values of $W_{p,tot}/w_P$ were computed from equation (13) for the propellant combinations considered using values of 0.30, 0.15, and 0.07 for the RP1-O_2, H_2-O_2, and H_2-F_2 cases, respectively. The results are presented in figure 6 which shows that the RP1 - O_2 case has the lowest specific weight with the H_2-F_2 case only slightly greater. The H_2-O_2 case is greater than the RP1 - O_2 case by approximately 100 percent while the H_2 case is greater by an amount on the order of 600 percent. Figure 6 also indicates the general specific size characteristics for the four propellant combinations.

It might again be noted that this is not a comparison of actual weights and sizes. Due to the impulse advantage of H_2, for example, the weight and size of the H_2 pump may be comparable to those of the corresponding RP1 and O_2 pumps in rockets having equal missions and payloads. This would occur because of the greatly reduced flow rate for the H_2 case.

E-301

TURBINE CONSIDERATIONS

The purpose of the turbopump drive turbine is, of course, to provide sufficient power to the pumps that the required pressure rise and flow rate are attained. As pointed out in a previous discussion, a minimum turbine flow rate is desired. Since the total power developed by the turbine is the product of flow rate times specific work output, it is then evident that these turbines will be high specific work output units.

The pertinent factors affecting the specific work output of the turbine can be discussed using the following equation:

$$\Delta h' = J\eta c_p T\left[1 - \left(\frac{1}{P_r}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{14}$$

From equation (14) it is evident that the specific work output is primarily a function of turbine efficiency, specific heat, inlet temperature, and the pressure ratio across the turbine. High efficiency is obviously desired because of its direct effect on $\Delta h'$. The influence of pressure ratio is illustrated in figure 7 where the ratio of ideal specific work output to turbine-inlet enthalpy which is considered a work potential and defined by the equation

$$\frac{\Delta h'_{id}}{h'} = \frac{\Delta h'/\eta}{c_p T} \tag{15}$$

is presented as a function of the ratio of inlet total pressure to exit static pressure P_r for $\gamma = 1.35$. Figure 7 indicates that up to pressure ratio values of 10 to 15 there is a rapid rise in work potential. As pressure ratios in excess of these values are used, however, not much additional potential is obtained. From figure 7 it is evident that, due to the desirability of high specific work output, high pressure ratios (10 and above) are desired.

If a pressure ratio is specified, together with a turbine limiting inlet temperature and turbine efficiency, then from equation (14) it is seen that specific work output will vary directly with the specific heat c_p of the turbine-drive fluid. Therefore, a comparison of the values of c_p for various turbine-drive gases will indicate the corresponding level of turbine specific work output. This property is presented in bar-graph form on the left portion of figure 8 for the propellant combinations being considered herein. They represent nominal values for a fuel-rich mixture with a turbine-inlet temperature of 1400° F. Comparison of the c_p values shows that the high-energy chemical propellants (H_2-O_2 and H_2-F_2) will develop a specific work output $3\frac{1}{2}$ times that of the low-energy propellant (RP1 - O_2). The H_2 case gives a corresponding value of approximately five times that of RP1 - O_2. Therefore, the turbines using the high-energy propellants will be relatively high specific-work-output units.

In order to determine the effect of propellant combination on the ratio of turbine flow rate to propellant flow rate, the relative power requirements must also be known. The pump discussion has shown that, for a given pump efficiency and pressure rise, the work required per unit pump flow is proportional to the specific volume of the fluid. Under similar specifications, the power required of the turbine per unit propellant flow rate is proportional to the bulk specific volume of the propellant, or the ratio of total volume being passed by the pumps to the total weight flow rate. In equation form

$$\nu_b = \nu_o\left(1 - \frac{w_f}{w_p}\right) + \nu_f\left(\frac{w_f}{w_p}\right) \qquad (16)$$

E-301

A comparison of the ν_b values then indicates the relative turbine power requirements. The values of ν_b for the propellant combinations are shown in the middle of figure 8. Again the RP1 - O_2 case is the lowest with the H_2-F_2 and H_2-O_2 cases succeedingly greater. The H_2 case is again much greater.

The turbine flow characteristics can now be investigated using the previously discussed relations that yields the equation

$$\frac{w_T}{w_P} = K \frac{\nu_b}{c_p} \tag{17}$$

The ratio ν_b/c_p is shown on the right of figure 8 for the four propellant combinations. Here it can be seen that the high-energy chemical propellants actually require less flow rate than the RP1 - O_2 case with the H_2-F_2 case being considerably less (approximately 1/2). Only the H_2 case requires more flow rate, being approximately $2\frac{1}{2}$ times that required for the RP1 - O_2 case.

The primary geometric differences among the drive turbines for the propellant combinations under consideration can be described by first considering the manner in which the turbine specific work output is obtained. The equation for turbine specific work output considering equal work per turbine stage is

$$\Delta h' = \frac{NU\Delta V_u}{g} \tag{18}$$

where U is the blade speed and ΔV_u is the change in whirl component of velocity across the stage at the mean section. If the diagram parameter $\psi = \Delta V_u/U$ is employed, then

$$\Delta h' = \frac{\psi NU^2}{g} \tag{19}$$

Now the selection of a value of ψ has an effect on η similar to that for pumps. This effect is illustrated in figure 9 where the ratio of η to a peak value is shown as a function of ψ. The efficiency reduces almost linearly from its maximum value as ψ is increased from unity. Because of the desirability of high efficiencies, low ψ values are therefore desired with representative values used ranging from 2 to 4.

E-301

Returning to equation (19) it is seen that, for a fixed value of ψ, $\Delta h'$ varies as NU^2. In order to minimize the number of stages, it is evident that high turbine-blade speeds are desired. Since there are, however, limiting values of U from rotor blade centrifugal stress consideration, U will be fixed at a maximum value. Finally, then, the variation in $\Delta h'$ reflects in the variation in the required number of turbine stages.

A comparison of stage number for the four propellant combinations can be made by referring to figure 8 which presents the c_p characteristics as representing the relative level of turbine specific work output. Using c_p as the basis, it can be seen that the H_2-O_2 and H_2-F_2 cases will require over three times the number of turbine stages as the RP1 - O_2 case. For the H_2 case six times the number of stages is required.

The turbines for the four propellant combinations are illustrated in figure 10 with the RP1 - O_2 case using a single-stage unit as a basis. The diameters of these turbines are scaled on a per unit propellant flow basis and obtained from an equation derived as follows: For similar stress requirements and gas-state conditions, the frontal area per unit turbine flow rate is related to the gas constant by the equation

$$\frac{A_{F,T}}{w_T} = K\sqrt{R} \tag{20}$$

Now

$$\frac{A_{F,T}}{w_P} = \frac{A_{F,T}}{w_T} \cdot \frac{w_T}{w_P} \tag{21}$$

So if equations (17) and (20) are substituted into equation (21) together with the relation

E-301

$$c_p = \frac{\gamma}{\gamma - 1} \frac{R}{J} \cong KR$$

the following equation for $A_{F,T}/w_P$ is obtained as

$$\frac{A_{F,T}}{w_P} = K \frac{\nu_b}{\sqrt{c_p}} \tag{22}$$

Equation (22) was then used to size the turbines in figure 10. The RP1 - O_2 and H_2-F_2 turbines are comparable in diameter with the H_2-O_2 and H_2 turbines increasing successively in size. Note again that these comparisons are on a per unit propellant flow basis and not for a given application. Therefore, a comparison of the turbines for a given application would require a knowledge of the actual flow rates for different propellants.

One additional turbine characteristic to be considered is its specific weight (weight per unit propellant flow). Turbine-weight studies have resulted in the following equation relating weight to stage number and size:

$$W_T = KN^{1/2} A_{F,T} \tag{23}$$

Using this equation together with equation (22) and the direct relation between N and c_p discussed previously it follows that

$$\frac{W_T}{w_P} = K\nu_b \tag{24}$$

E-301

Thus comparison of the weight characteristics can be made by referring to figure 8 where ν_b is compared. From this comparison, it is evident that some penalty in specific weight is required for the high-energy chemical propellants with a considerable penalty paid for the H_2 case.

ARRANGEMENT AND GEARING CONSIDERATIONS

The final turbopump factors to be considered in this paper will be the turbopump arrangement and associated gearing considerations. The arrangement, which involves the manner in which the pumps and turbine are connected, can be discussed by referring to the findings in the pump and turbine sections. There it was found that the high-density fluids (RP1, O_2, F_2) desired a relatively low blade speed, whereas for the H_2 pump and all drive-turbines high blade speeds were desired. The resultant turbopump arrangements that appear attractive from this consideration are shown in schematic form in figure 11. For the RP1 - O_2 case, gearing to both pumps is desired. For the H_2-O_2 and H_2-F_2 cases gearing to the oxidizer pumps appears best. Similarly, for the H_2 case direct drive appears to be best.

These different gearing arrangements can be used to determine whether the gearing problem will be more severe for the high energy propellants than for the low. The basis for comparison will be the power to be transmitted to the pumps through the gearing. A comparison of this power requirement can be made using the following equations. For the RP1 - O_2 case:

$$\frac{P_G}{w_P} = K\left[\nu_o\left(1 - \frac{w_f}{w_P}\right) + \nu_f \frac{w_f}{w_P}\right] = K\nu_b \tag{25}$$

since all the power is transmitted through gearing. For the high-energy chemical units

$$\frac{P_G}{w_P} = K\nu_o\left(1 - \frac{w_f}{w_P}\right) \tag{26}$$

since only the oxidizer-pump power is being transmitted. For the H_2 case, of course,

E-301

$$\frac{P_G}{w_P} = 0 \tag{27}$$

The results of calculations made with these equations is shown in bar-graph form in figure 12. The figure shows that the specific power transmitted for the high-energy chemical propellants is less than that for the low-energy propellant (zero for the H_2 case). Therefore, based on specific power, a less severe gearing problem is indicated. In the actual case, this difference is even more pronounced due to the flow rate of the high-energy propellants being considerably less than that of the low-energy propellants.

It might be noted that, in cases where low hydrogen-tank pressures are used, direct coupling between the turbine and hydrogen pump would result in a turbine of such size and weight that gearing a smaller turbine to this pump would result in a lighter over-all turbopump weight. The final selection would be based on consideration of not only weight but also complexity and reliability at the increased gearing power levels.

CONCLUDING REMARKS

This paper has presented a discussion of turbopump characteristics for high-energy propellants. Significant conclusions of this study are as follows:

E-301

1. The turbopumps for the high-energy propellants utilizing hydrogen as the fuel appear larger and heavier on a unit propellant-flow basis than for the conventional turbopumps. However, the actual turbopump size and weight may be equivalent to the conventional turbopump due to the considerably reduced flow rate occurring as the result of the higher impulse.

2. Because of the high specific volume of liquid hydrogen, hydrogen pumps are basically high-power and high-blade-speed units. This high-speed characteristic makes direct drive between the turbine and the hydrogen pump attractive.

3. Turbines with multiple stages are required for the high-energy propellant applications to achieve high efficiency and thus low turbine flow rates.

E-301

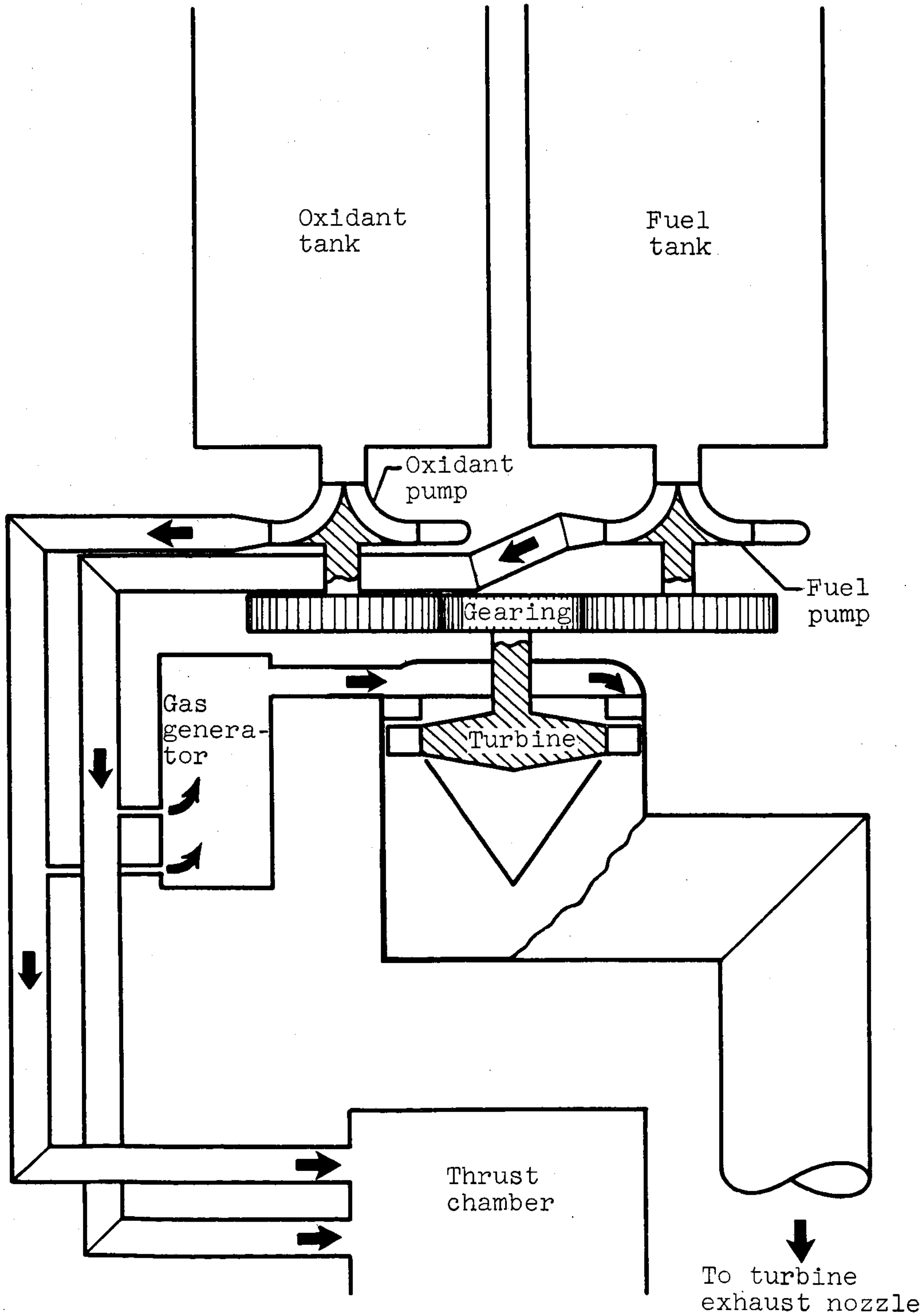


Fig. 1. - Schematic diagram of typical turbopump system.

E-301

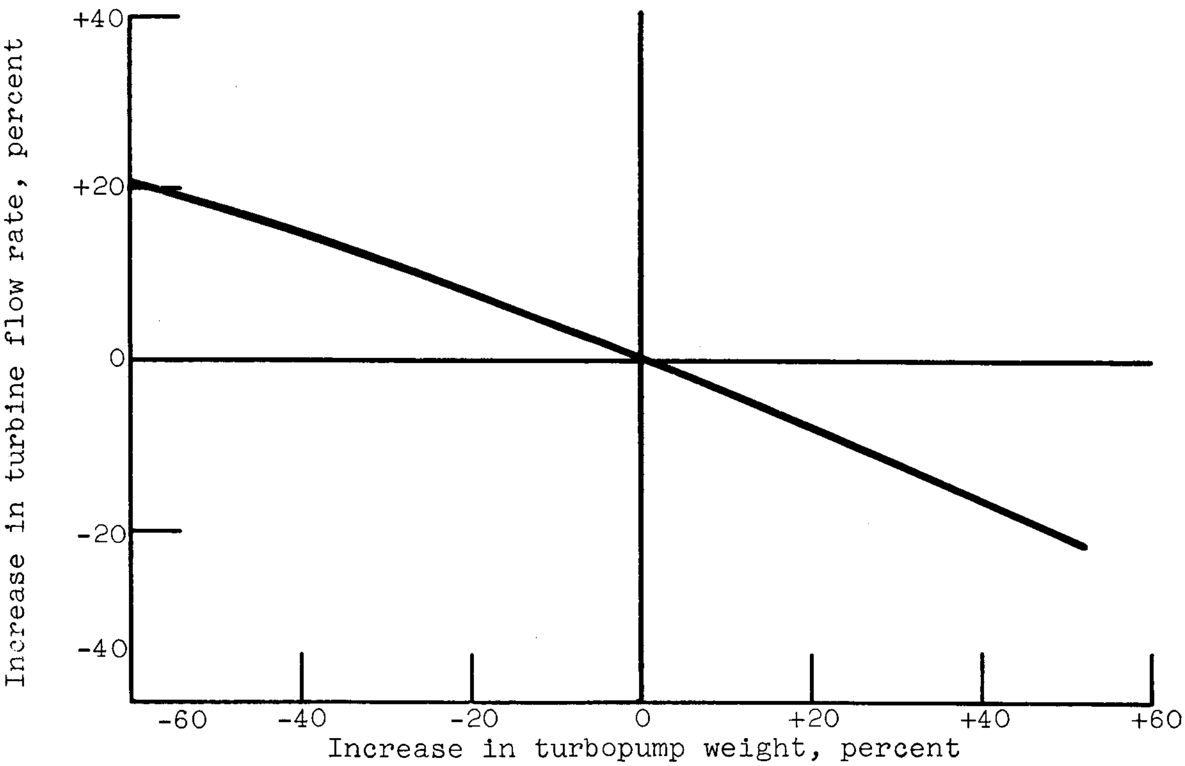


Fig. 2. - Example significance of turbopump weight and turbine flow rate for a given ratio of rocket payload to gross weight.

E-301

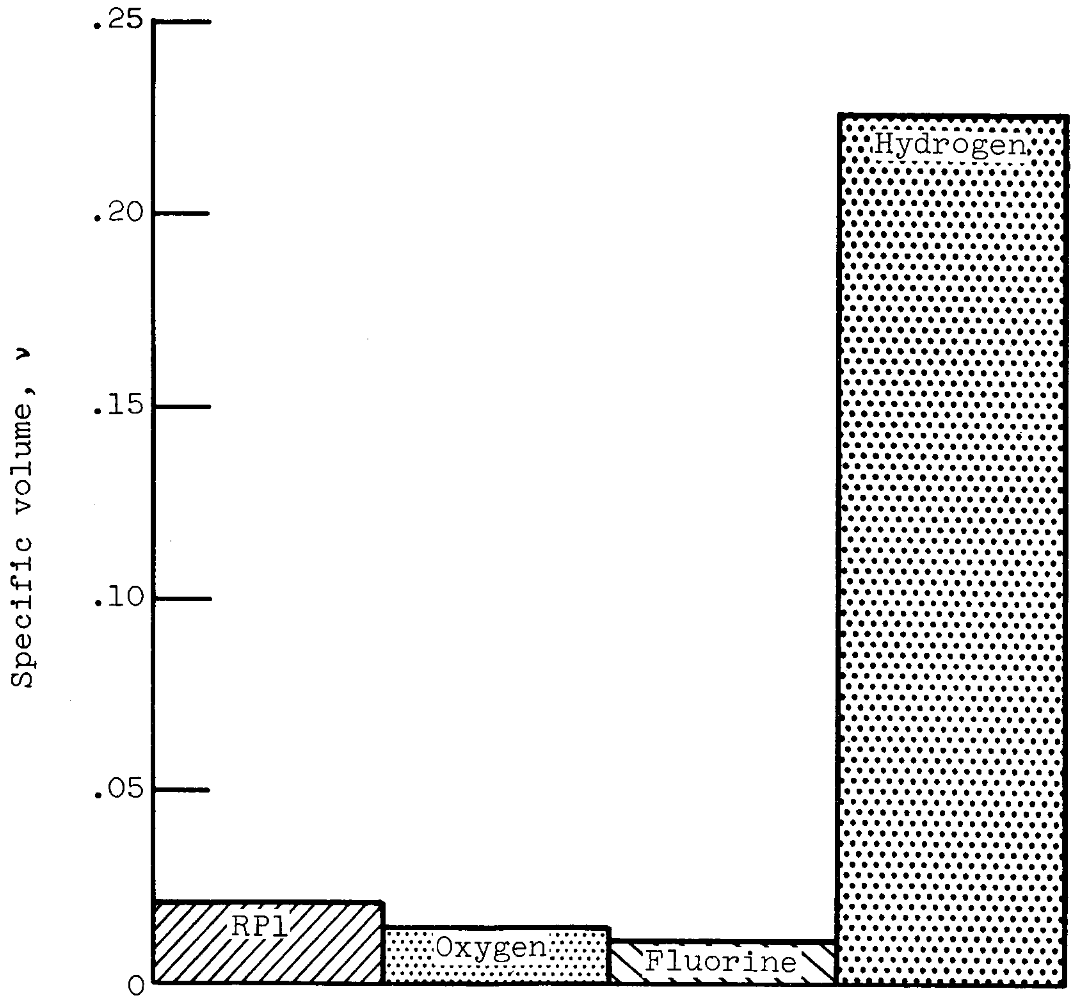
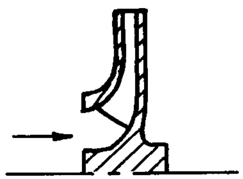
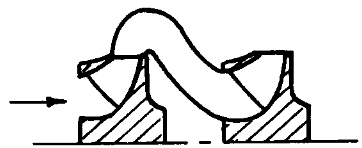


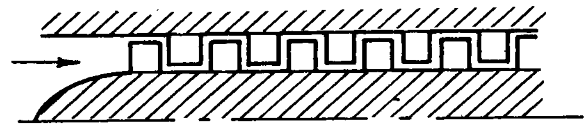
Fig. 3. - Comparison of propellant specific volumes.



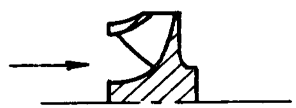
(b) Single-
stage hydro-
gen pump.



(c) Two-stage
hydrogen pump.



(d) Hydrogen pump with numerous
axial stages.



(a) RP1, oxygen,
and fluorine.

Fig. 4. - Effect of fluid used on pump configuration.

E-301

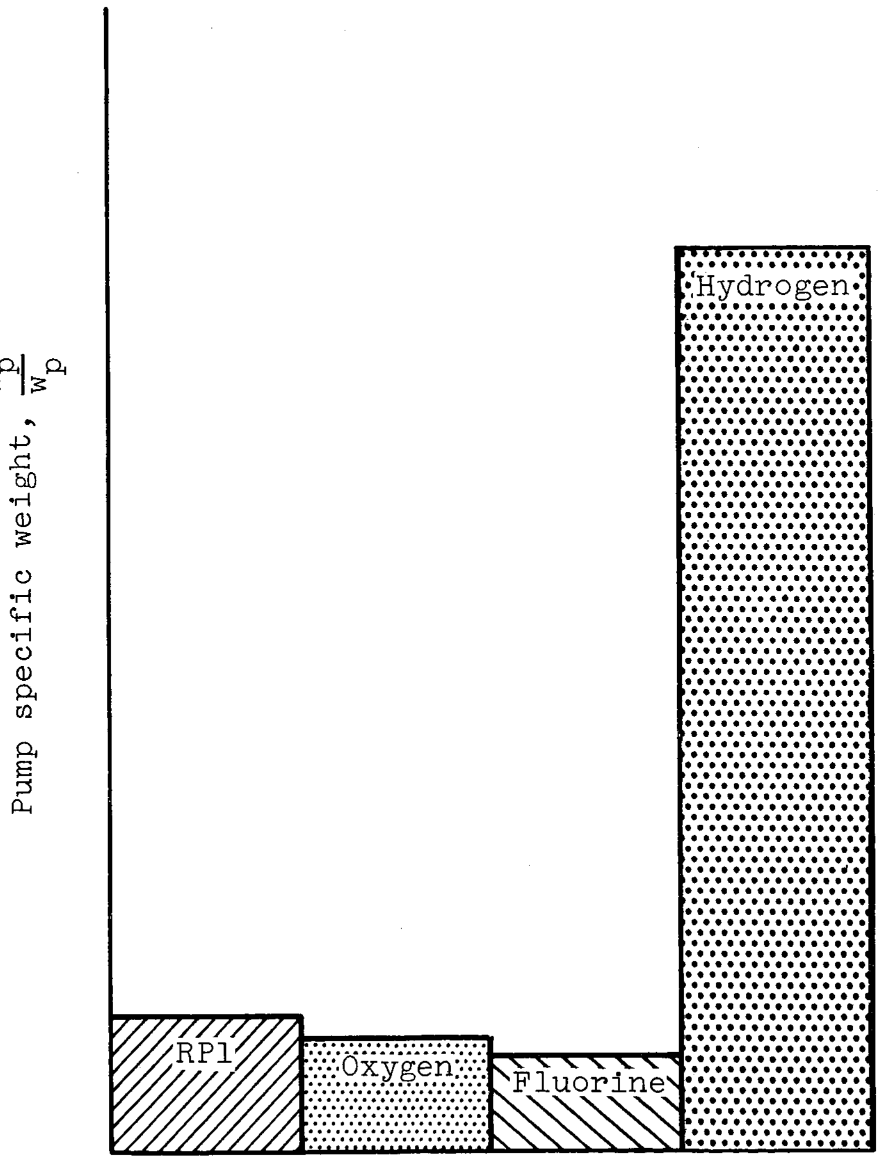


Fig. 5. - Effect of propellant on pump specific weight.

E-301

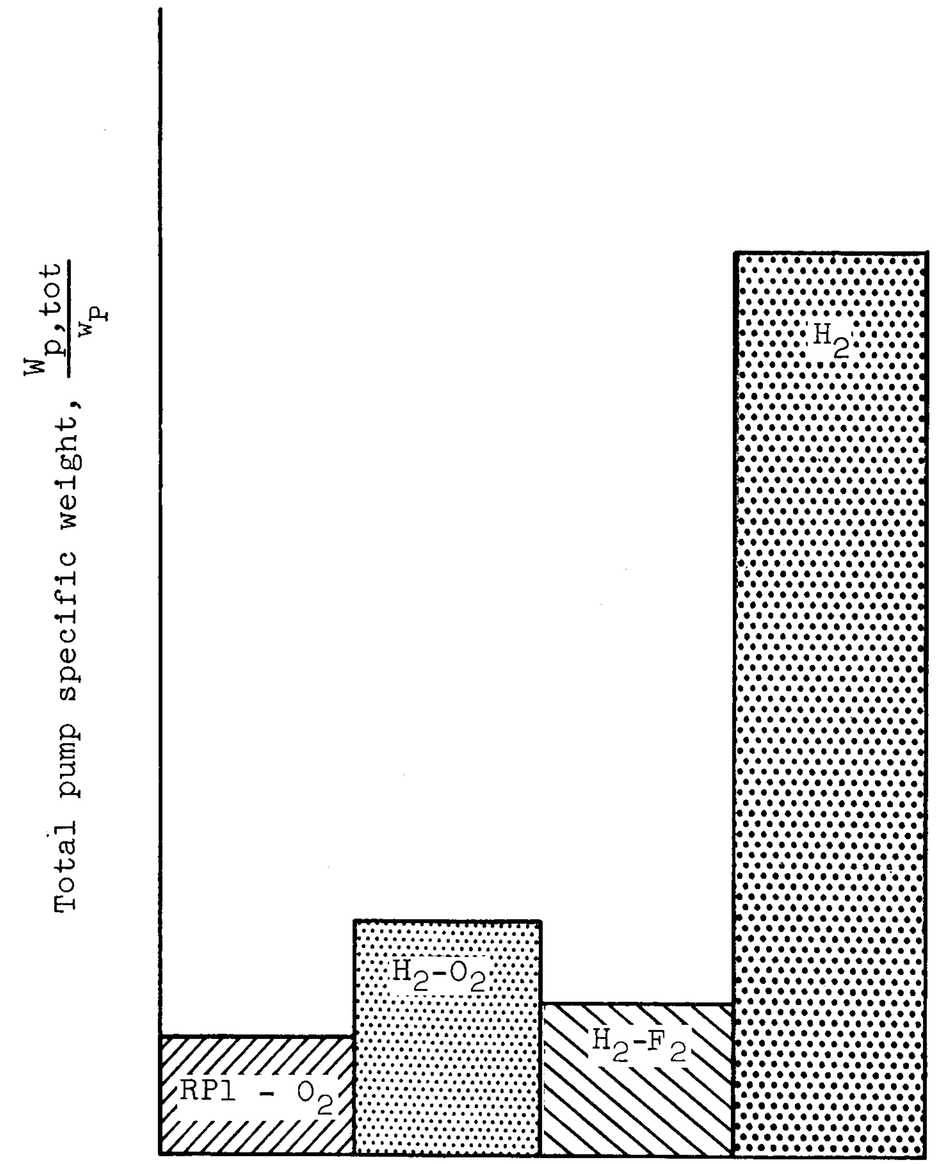


Fig. 6. - Effect of propellant combination on total pump specific weight.

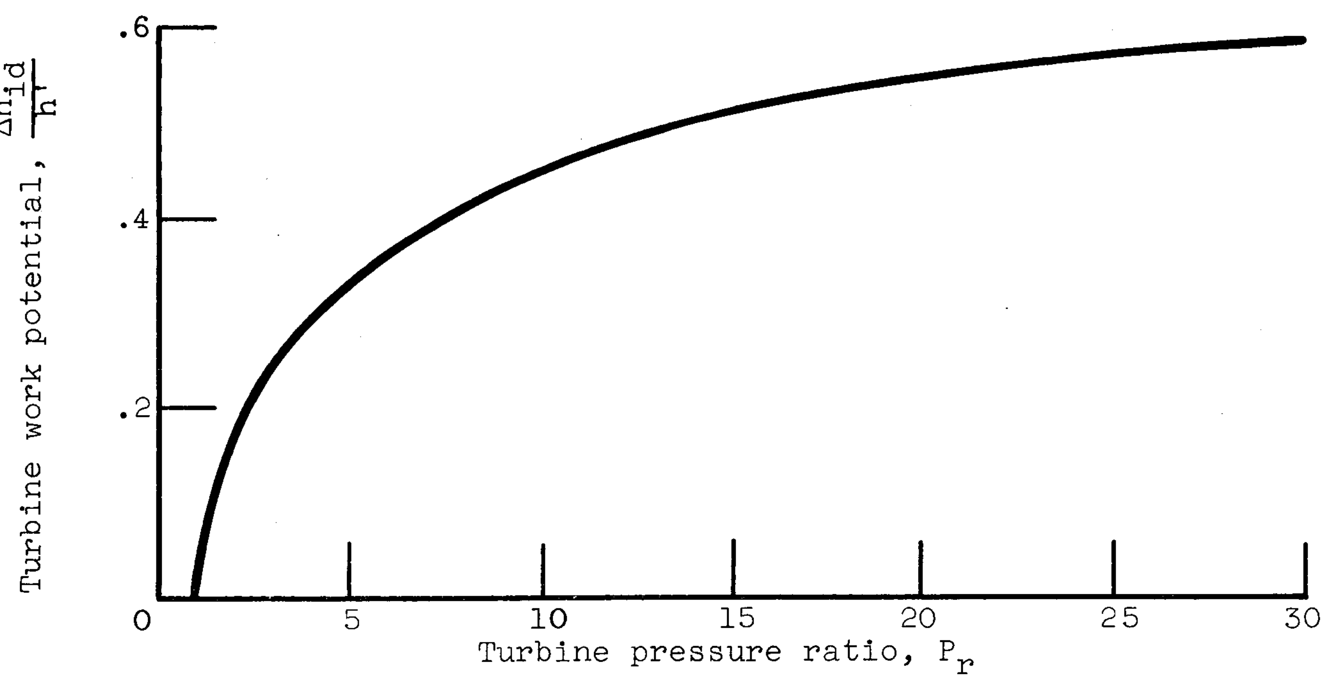


Fig. 7. - Example effect of turbine pressure ratio on turbine work potential.

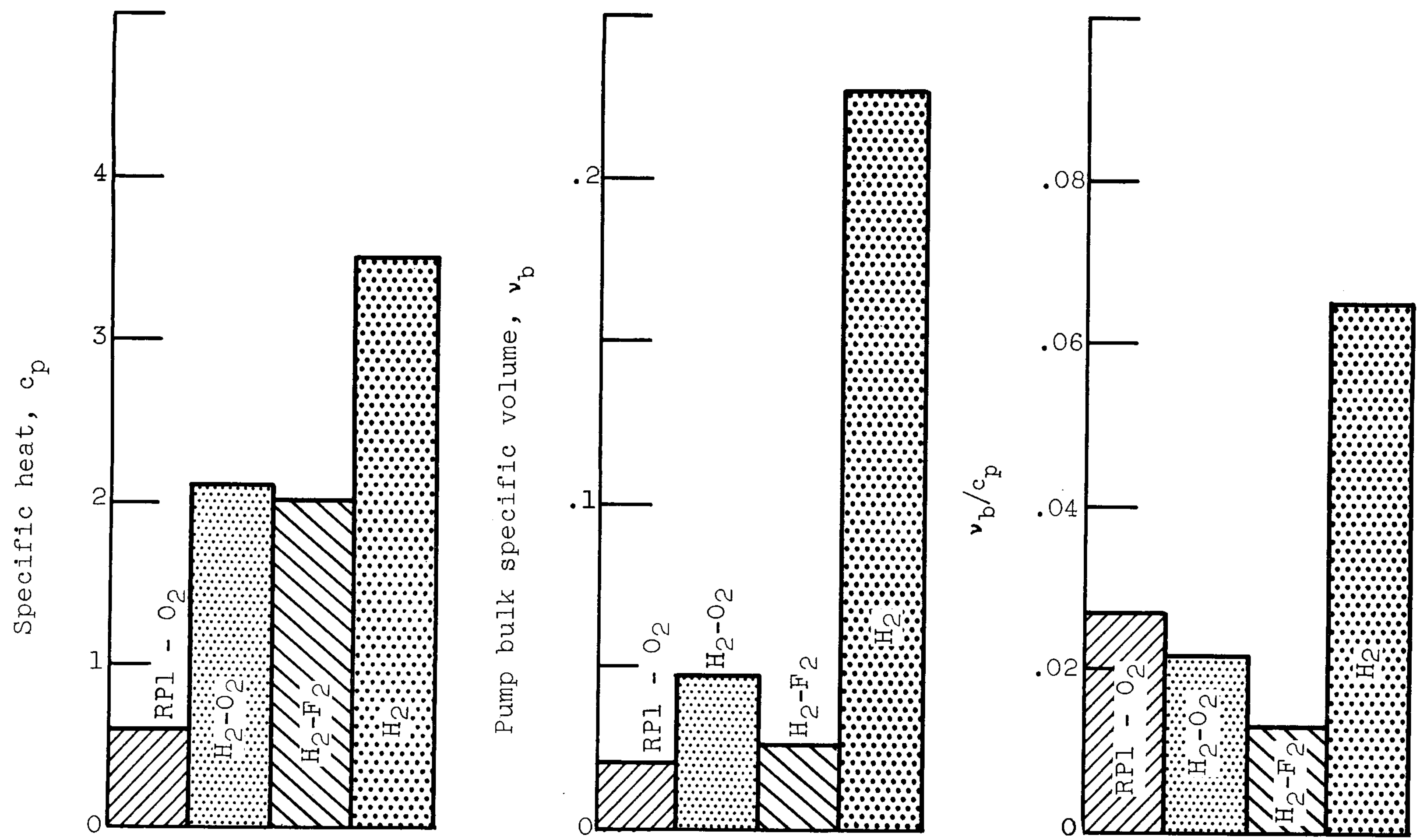


Fig. 8. - Factors affecting turbine power and flow rate.

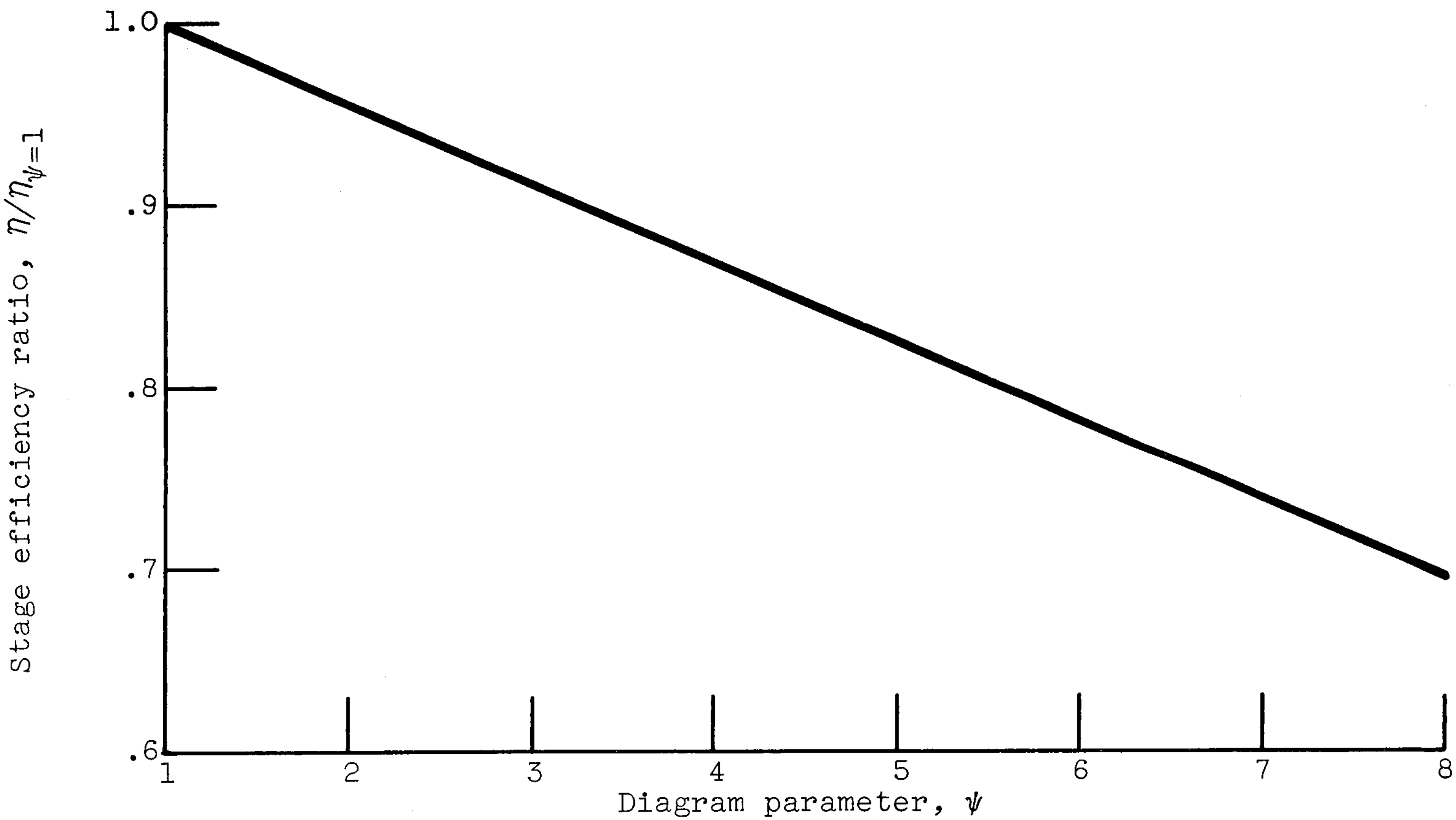


Fig. 9. - Influence of turbine stage diagram parameter on stage efficiency.

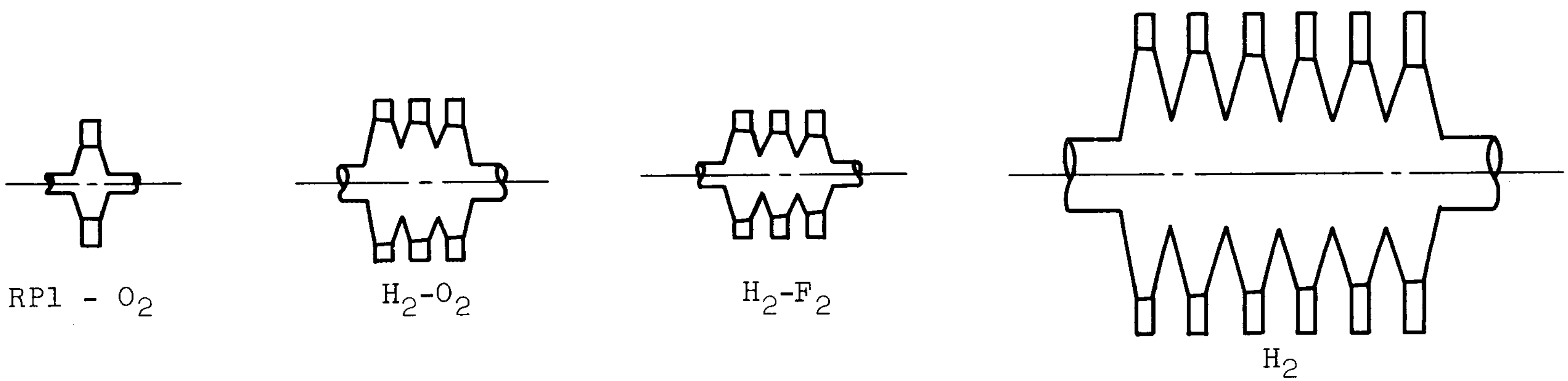


Fig. 10. - Effect of propellant combination on turbine configuration.

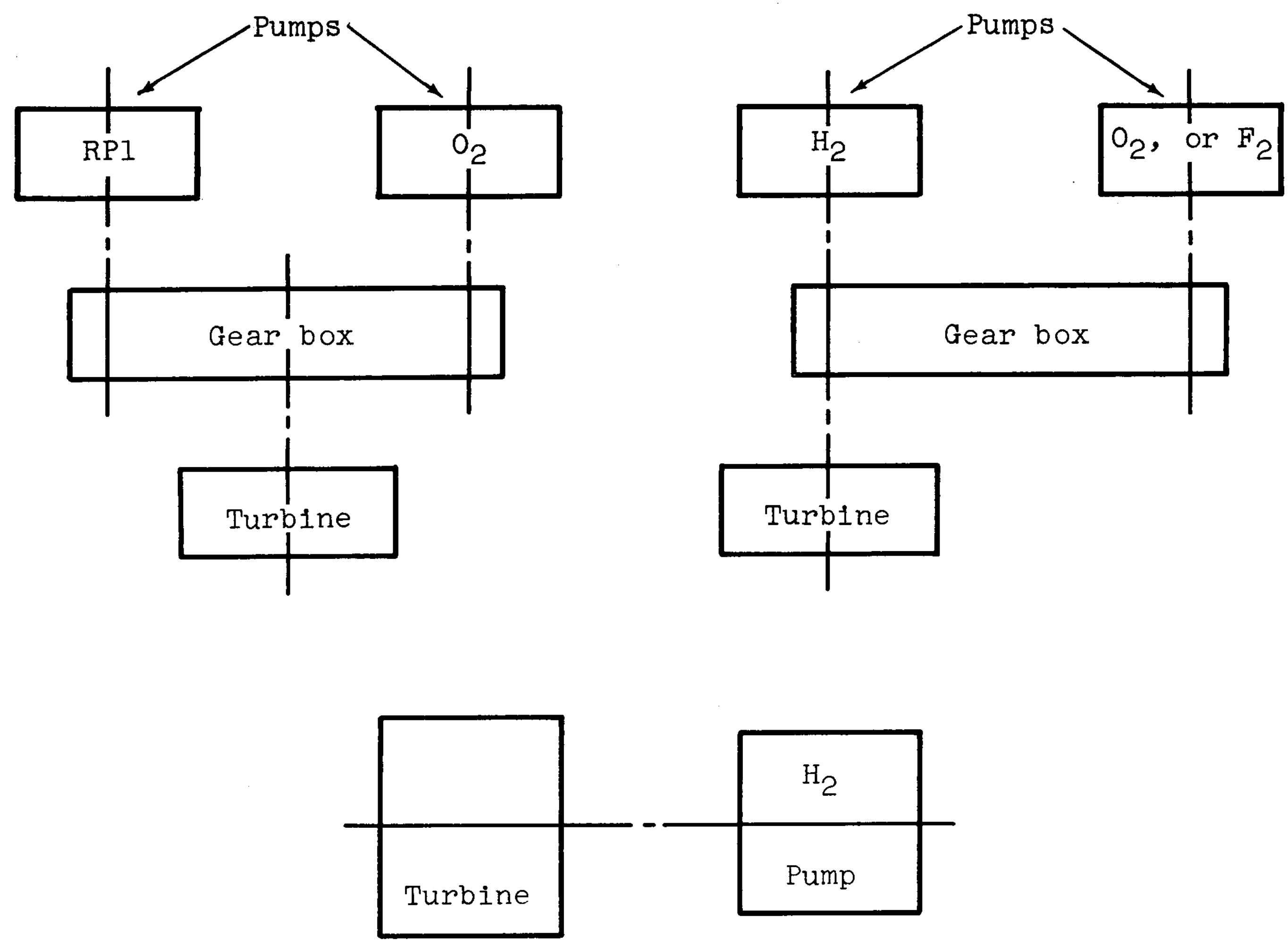


Fig. 11. - Comparison of arrangements for high- and low-energy propellants.

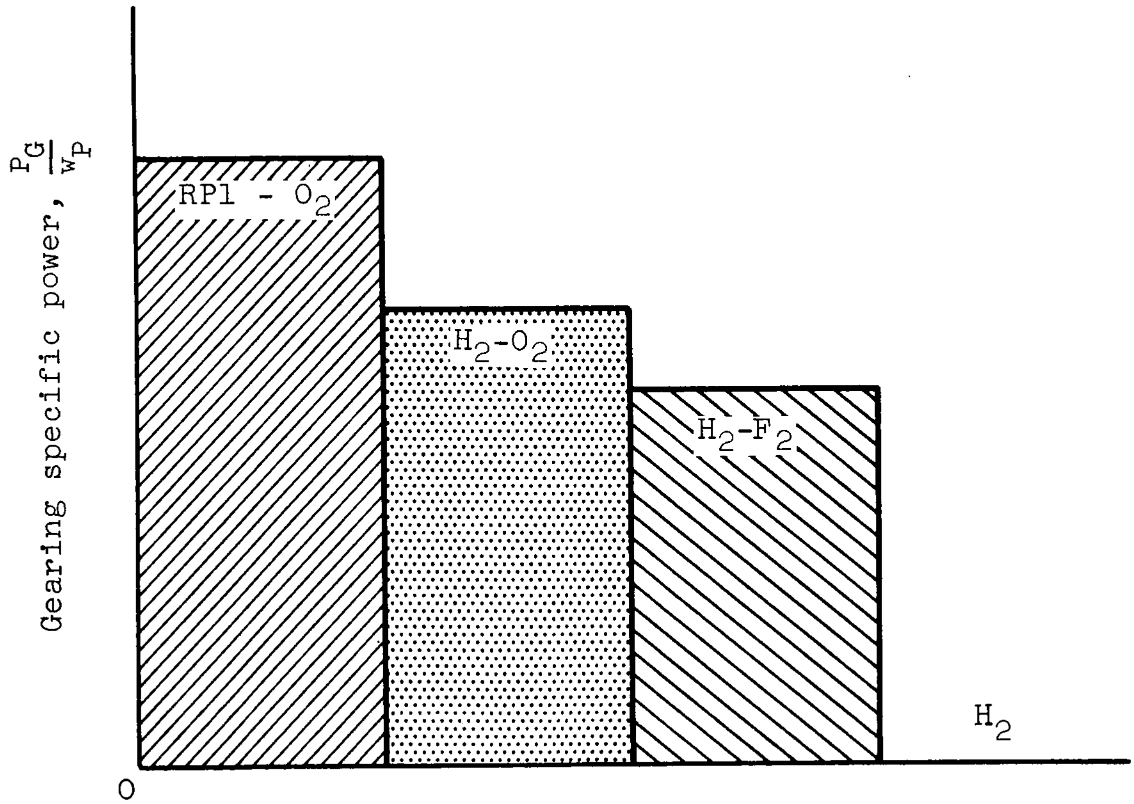


Fig. 12. - Comparison of gearing specific power requirements.

NASA-CLEVELAND, OHIO E-301